Analysis and Design Considerations for the Right Half -Plane Zero Cancellation on a Boost Derived dc/dc Converter

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***Abstract*— A boost derived topology, the two inductor boost with switch near ground presents some advantages over the conventional boost topology like continuous output current and MOSFET near ground [1]. The main advantage of this new topology is that the right half-plane (RHP) zero (inherent to the boost topology) can be cancelled by means of a new energy transference principle. This work presents a dynamic study of the topology and it shows that the RHP zero cancellation is not achieved for all design cases. The aim of this work is to develop a model for this topology in order to analyze the design requirements to obtain the RHP zero cancellation. A design condition has been derived from the dynamic analysis for achieving minimum phase characteristics on the new boost topology. The model and conclusions have been validated by means of an actual prototype. Considerations about the influence of the theoretical condition on the design and the field of application of this topology are shown in this paper.**

I. INTRODUCTION

The boost converter is a well-known and simple topology which is widely used in many applications. Its main limitation on CCM is the dynamic response because of the RHP zero effect, which reduces the bandwidth of a converter approximately to one third of the RHP zero's frequency [2].

Several modifications have been proposed in the boost topology to overcome the drawback of the RHP zero as in [1], [3] and [4]. In [1], a two inductor boost topology was introduced to eliminate the RHP zero. This topology proposes a new energy transference principle by means of an additional inductor coupled to the boost inductor breaking the uncoupling between the input and the output of the converter. This new energy transference principle allows to derive a new boost converter without RHP zeros, but this effect depends on some design parameters.

The purpose of this paper is to analyze in detail the two inductor boost topology proposed in [1] to determine the theoretical condition to achieve RHP zero cancellation.

The content of this paper is:

- Development of the averaged model of the new boost topology.
- Analysis of the theoretical condition for RHP zero cancellation.
- Analysis of the coupled inductors' turns ratio on the performance of the converter.
- Analysis of the RHP zero cancellation condition on the design.
- Validation of the RHP cancellation condition based on an actual prototype

II. NEW BOOST TOPOLOGY ANALISYS

In order to obtain a boost converter without RHP zero, the two inductor boost converter [1] introduces a new energy transference principle which leads to a new boost topology (Figure 1) that has the following characteristics:

- The same dc gain as the conventional boost converter $V_{out}/V_{in}=1/(1-d)$.
- One additional winding, coupled to the input inductor, which makes possible the energy transference between the input and the output of the converter during the ON period of the main switch and, as a consequence, the RHP zero elimination.
- An additional inductor at the output, which produces continuous current. This is another advantage of this topology over the conventional boost.
- The MOSFET is grounded, which is an advantage to other RHP cancellation boost solutions.

A boost derived converter with these characteristics, presented in [1], should provide a minimum phase system without the RHP zero bandwidth limitations.

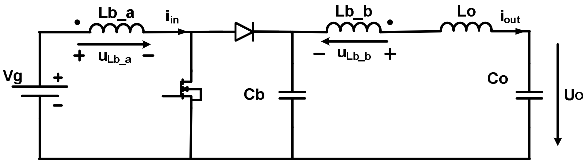

Figure 1. Schematic of the new boost converter

A detailed study of this topology shows that for high turns ratio of the coupled inductors $n=U_{Lb\_a}/U_{Lb\_b}$ both Lb_b and Lo sizes are reduced for the same specifications. Also the input and output current ripple are reduced. Hence, from the electrical point of view, the value of the turns ratio should be as high as possible in the design, in order to reduce the magnetic components of the converter. This effect can be seen in the expressions (1) and (2),

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where the input current ripple depends not only on the inductance Lb_a but also on the inductance Lo and the turns ratio n. This fact is especially significant in several applications, especially in aerospace, where size and weight are critical parameters. Another consequence obtained is that there is one degree of freedom in the design, because the same input and output current ripples can be obtained with different combinations of Lb_a, n (turns ratio) and Lo (three parameters).

$$\Delta i_{in} = U_{Lb\_a} \cdot d \cdot T \cdot \left(\frac{1}{Lb\_a} + \frac{1}{Lo \cdot n^2} \right) \quad (1)$$

$$\Delta i_{out} = \frac{U_{Lb\_a}/n \cdot d \cdot T}{Lo} \quad (2)$$

III. Dynamic Characterization of the New Boost Converter

First of all, the averaged model of this topology has been developed and implemented in Orcad Pspice to check its dynamic characteristics. Figure 2 shows the averaged model of the new boost topology.

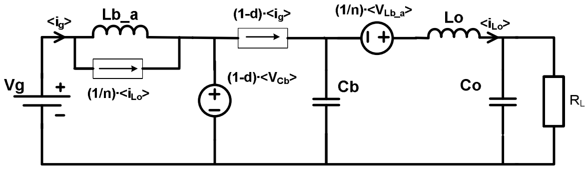

Figure 2. Averaged model of the new boost topology

In order to obtain a theoretical verification of the simulations' results in the frequency domain, the analytical expression for the duty cycle to output voltage transfer function has been derived based on the state-space equations of the converter [5], [6].

The state-space equations of the linearized system are:

$$\dot{\tilde{x}} = A \cdot \tilde{x} + B \cdot \tilde{d} + E \cdot \tilde{v}_g \quad (3)$$

$$\tilde{v}_o = C \cdot \tilde{x} \quad (4)$$

The state vector and the matrices of the system are shown in (5), (6), (7) and (8).

$$\tilde{x} = \begin{pmatrix} v_{Cb} \\ i_{Lb\_a} \\ v_o \\ i_{Lo} \end{pmatrix} \quad (5)$$

$$A = \begin{pmatrix} 0 & \frac{1-d}{C_b} & 0 & \left(\frac{1-d}{n} - 1\right) \cdot \frac{1}{C_b} \\ -\frac{1-d}{L_{b\_a}} & 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{R \cdot C_O} & \frac{1}{C_O} \\ \left(1 - \frac{1-d}{n}\right) \cdot \frac{1}{L_O} & 0 & \frac{-1}{L_O} & 0 \end{pmatrix} \quad (6)$$

$$B = \begin{pmatrix} \frac{-i_{in}}{C_b} \\ \frac{v_{out}}{L_{b\_a}} \\ 0 \\ \frac{v_{out}}{L_o \cdot n} \end{pmatrix} \quad (7)$$

$$C = (0 \quad 0 \quad 1 \quad 0) \quad (8)$$

Solving the equations (3) and (4), the transfer function of duty cycle to output voltage is obtained from the expression (9).

$$G(s) = C \cdot (s \cdot I - A)^{-1} \cdot B \quad (9)$$

The transfer function's analysis shows a two grade numerator and a four grade denominator. Analyzing the denominator, there are two complex conjugated solutions on the left half plane, which means stable poles. The numerator is a two order polynomial with two zeroes which are on the left or right half plane depending on the following expression:

$$d + n < 1 \quad (10)$$

Based on the condition (10) , it is obtained that if the addition of the duty cycle value (d) and the turns ratio (n) (two dimensionless quantities) is less than unity, then the transfer function of duty cycle to output voltage has two zeroes on the left half-plane. This implies a two order system response (two poles) and additionally a double pole-double zero. For values of d+n greater than unity, the two RHP zeroes are not cancelled and, as a result, the converter's bandwidth is limited. Therefore, condition (10) should be satisfied to have a boost converter with improved dynamic performance.

An example of the influence of the turns ratio on the dynamic response is in Figures 3 and 4. Firstly, the turns ratio will be set to n=2 (d+n>1 for any duty cycle), greater than unity in order to reduce the inductances of the magnetic components.

The Bode plots of duty cycle to output voltage obtained with the averaged model are shown in Figures 3 and 4. It can be noticed that for d+n>1 at high frequency the phase falls down to -540º (Figure 3) and the magnitude has a decreasing slope of -40dB/dec. As a result, the converter's transfer function has four poles and two RHP zeroes.

Therefore, for this design, minimum phase characteristics are not achieved.

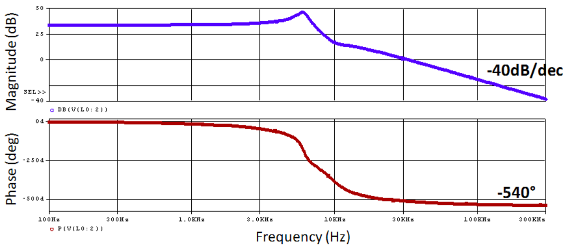

Figure 3. Simulated bode plots of the new boost converter for a turns ratio n=2

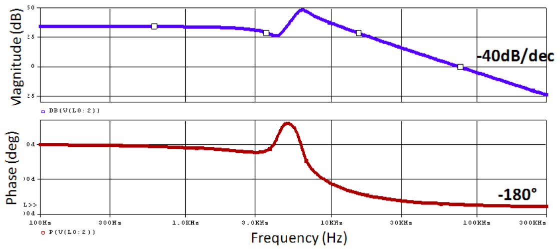

Figure 4. Simulated bode plots of the new boost converter for a turns ratio n=0.4

For a turns ratio value less than unity, n=0.4 (d+n<1) and a duty cycle smaller than 0.6, the Bode plots of Us/d have been calculated and shown in Figure 4, with a fall of 180º in phase and a negative slope of magnitude of 40dB/dec, which means a transfer function with two poles and a double zero-double pole. For this design, there is a second order response of the output voltage, without the RHP zero effect which is the expected dynamic response.

IV. DESIGN OF A TWO INDUCTOR BOOST WITHOUT RIGHT HALF-PLANE ZERO

The two inductor boost converter prototype has been designed for an actual application with the following specifications: Maximum power of 280W, input voltage from 20V to 30V and output constant voltage of 36V.

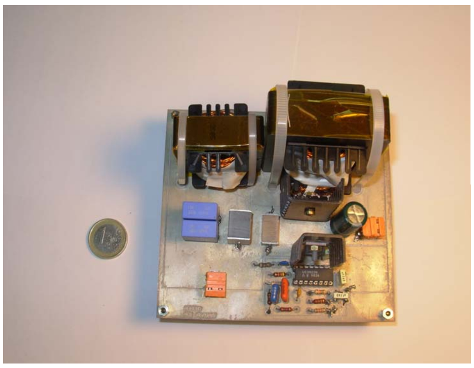

Figure 5. Photograph of the Two Inductor Boost Prototype

As the theoretically maximum duty cycle is $d_{máx}=0.44$, the turns ratio selected should be lower than $1-d_{máx}=0.56$ (in order to keep d+n<1). Finally, with a security margin, the chosen turns ratio was 0.45.

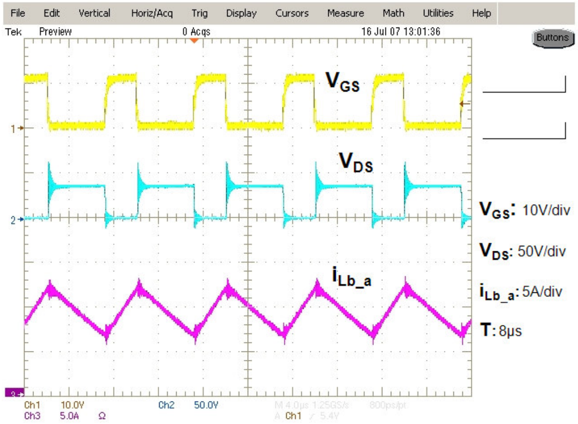

Figure 6. Waveforms measured on the Two Inductor Boost Prototype

This new topology will be a good design option, in general, instead of any other boost topology, for applications where a high bandwidth is needed and also weight and volume of the converter are not critical design parameters, although for certain specifications the new boost converter can be optimized with regard to the conventional boost design.

V. EXPERIMENTAL RESULTS

First of all, the bode plot of duty cycle to output voltage has been measured and compared to the simulated bode plot of the averaged model. Figures 7 and 8 show that magnitude and phase of the averaged model and the measurement are in good agreement for all frequencies.

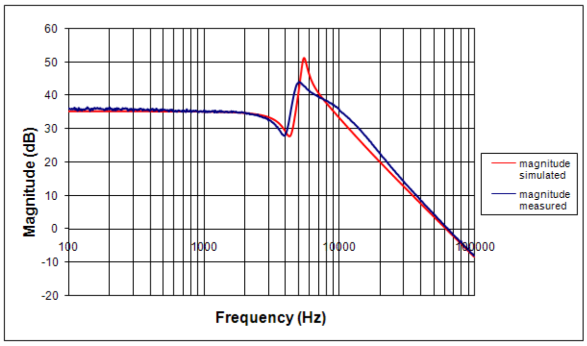

Figure 7. Measured and simulated bode plots of magnitude of duty cycle to output voltage transfer function

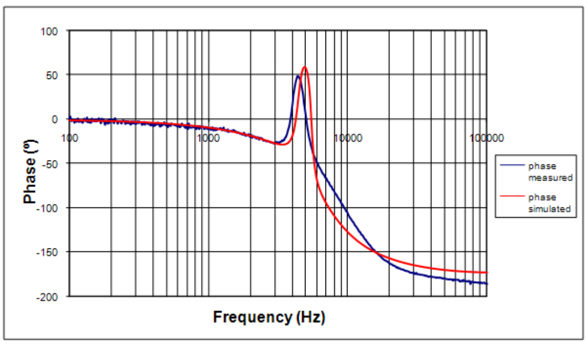

Figure 8. Measured and simulated bode plots of phase of duty cycle to output voltage transfer function

The conditions for the measurements shown on Figures 7 and 8 are: output voltage of 36V, output power of 280W, duty cycle d=0.32 and a frequency of 125kHz. Turns ratio is n=0.45.

Once the averaged model has been validated with the constructed prototype, the next step is the validation of the condition (10) for RHP zero cancellation on the new boost converter. The duty cycle has been increased to d=0.55 in order to reach condition (10).The parameters for this test are: output voltage of 20V, output power of 75W and a frequency of 125kHz. Turns ratio is n=0.45.

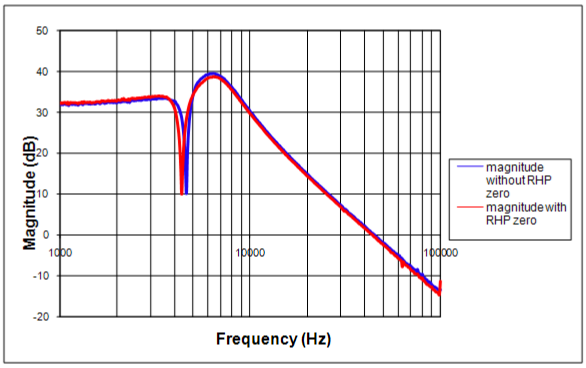

Figure 9. Measured and simulated bode plots of magnitude of Us/d

Then it will be compared the bode plots of the converter when the duty cycle is slightly over and under the limit value. On the first test, the value of d+n is higher than one so a non minimum phase characteristic should be measured, with two RHP zeroes. On the second test, with d+n<1, a bode plot with a double pole-double zero and no RHP zeroes should be measured.

As the difference in the duty cycles in both cases is very small, the magnitude bode plots should be very similar. On the other hand, the phase characteristics should be different as a result of the RHP zeroes effect for d+n>1. Figures 9 and 10 show the results of the test, which are satisfactory, and the theoretical condition for the RHP cancellation has been validated.

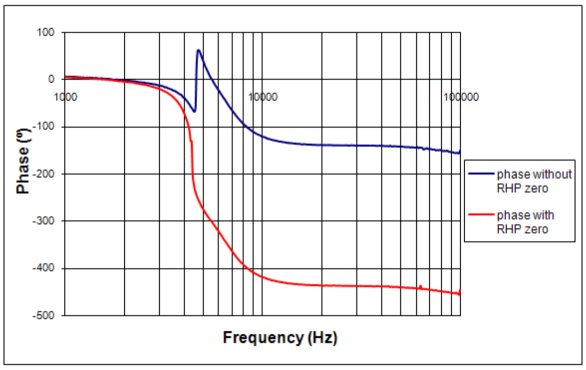

Figure 10. Measured and simulated bode plots of phase of Us/d

VI. CONCLUSION

A detailed analysis of the two inductor boost with switch near ground topology has been performed. This topology has several advantages over conventional boost topology, mainly in its dynamic performance. It has been characterized the theoretical condition for RHP zeroes cancellation. The condition d+n<1 has been identified as the responsible of the RHP zero elimination. This is the main contribution of this paper. It also has been analyzed the influence on the electrical design of applying this condition (d+n<1), and the field of application of the new boost topology has been studied. A 280W prototype has been built and the design condition for the RHP zeroes cancellation has been validated.

VII. REFERENCES

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